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The Upgrade of the LHCb Detector

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The LHCb experiment aims at determining with a high precision the CP-violation parameters and at studying rare decays of B hadrons. Until 2015, a couple of fb^{-1} will be recorded. This may be sufficient to see the first evidence for an extension to the standard model at LHC, but, if its effects are weak, we may have to increase the statistics. Even if a clear signal is observed already, this sample will not permit to understand this new physics. Thus, it is foreseen to upgrade the accelerator and detectors from 2015 to increase the luminosity and improve the performances of the experiments. The LHCb collaboration started to work on the optimisation of its detector to increase its capabilities at high luminosity and in more difficult conditions linked to the a far higher collision rate. This paper presents the main physics motivations of the collaboration and the most important modifications to the detector design.

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1. Introduction

The LHCb experiment [1] is one of the four large experiments at the LHC. The detector started to record pp collisions from accelerator day-one. This marked the beginning of its wide physics program. The experiment is dedicated to the search of new physics via the precise study of CP-symmetry violation and rare decays of B hadrons and by recording an enormous amount of beauty and charmed hadrons. It benefits from the large $b\bar{b}$ cross-section at the LHC which is supposed to reach up to 500μb at 14TeV and from the production of all B hadrons species. LHCb is a single arm spectrometer covering an acceptance ranging from 15 up to 300×250mrad motivated by the fact that at high energies both quarks from the $b\bar{b}$-pairs are predominantly produced at small angles with respect to the beam. The originally foreseen luminosity is 2×10^{32}cm^{-2}.s^{-1}, leading to the production of about 10^{12} $b\bar{b}$ pairs per year[1]. The plan for the upgrade is to increase the luminosity in two steps, first by a factor 5 and in a second phase by a factor 10 or 20. An integrated luminosity of 50fb^{-1} is supposed here for the first step. The upgrade should take place during the long shutdown scheduled to improve the accelerator and detectors in the period 2015-2016. This article focuses essentially on the first phase, the physics case being first considered, the requested and planned LHCb optimisation is described afterwards. The flavour sector is very sensitive to new physics as it depends heavily on processes implying virtual particles in b or c quarks decay. It may therefore be possible to find deviations to the standard model although searches cannot directly produce the corresponding particles. Moreover, the properties of the extensions to the model standard that may be seen at LHC may only be understood by looking at different aspects of the new phenomenon. Finally, LHCb aims at measuring with an unprecedented precision the parameters of CP-violation in order to guide the theory towards a clearer answer to the pending questions related to this mechanism. If the new physics effects are weak and after a few fb^{-1}, the gain in running at constant luminosity becomes small and increasing the luminosity is a necessity. Apart from the excellent beam conditions and the high rate in the apparatus solid angle, the present detector is built to satisfy a certain number of requirements common to most of the modern heavy quark experiments and which are :

- A precise vertexing in order to identify displaced decay points and have a good reconstruction of the tracks up to the interaction point.
- An efficient particle identification as the kinematic constraints do not permit alone to remove background contributions to the decay modes.
- The selection of events of interest by the trigger is crucial especially at hadron colliders to provide a large efficiency and the smallest possible contamination.
- The acquisition has to cope with a large rate in order to provide large statistics for the offline analysis.

The LHCb upgrade studies lead to a full re-optimisation of the detector and a new design of some of its constituents. The present LHCb trigger relies on three levels of decisions. The first one (L0) is a hardware trigger based on a few sub-detectors (pile-up, calorimeter and muon systems)

[1] A year is defined by 10^7s.

reducing the rate down to 1MHz and followed by two software levels. The L0 is a bottleneck in the system at large luminosity as the collision rate will reach 30MHz. It is planned to overcome the hardware trigger and send at 40MHz the data though the acquisition to a purely software trigger. The goal is also to have the maximum flexibility in order to adapt any new physics signal and to improve the trigger efficiency especially in the hadronic channels where a gain by a factor 2 is expected. The requested PC farm would reach 16000 processors giving on average 0.4ms to reduce the background by a factor 10^5 and maximise the efficiency. Such an acquisition leads to a new design of the front-end electronics of the sub-detectors (the muon system modification is not so drastic as for the others) in order to send the events at 40MHz instead of the present 1MHz rate. The vertexing, tracking and particle identification will also be modified in order to improve the overall detector capabilities in a large occupancy environment where the radiation levels will be more difficult to cope with.

2. Potential for physics discoveries at an upgrade

LHCb started to operate in very satisfactory conditions and the race for data collection started. Nevertheless, it seems clear that a maximum of 5-7 fb^{-1} will be produced by the end of 2015. Some key measurements may be performed and lead to interesting results. The possible observation of rare decays such as $B_s \to \mu\mu$ is one of those even if the expected luminosity should not permit to go down to the standard model branching ratio. The mixing phase $\phi_s = -2\beta_s$ in the $B_s \to J/\psi\phi$ decay should be well known, if it is larger than the standard model expectations.

Determination of the mixing phase ϕ_s in the $B_s \to J/\psi\phi$ decay mode : The phase ϕ_s of the B_s mesons is well predicted in the standard model framework[2], $\phi_s = -0.036 \pm 0.002$rad and directly constraints the CKM unitarity triangle through its proportionality to η. CP violation occurs in $B_s \to J/\psi\phi$ by the interference of decays with and without mixing. This mixing involves box-diagrams where new particles may easily enter and enhance CP violation up to mixing values far larger than the standard model predictions. Nevertheless, this present value requires a precise experimental determination. After 2fb^{-1}, the monte carlo studies show that a precision of 0.03rad may be reached [3]. Simply scaling the errors up to 50fb^{-1} leads to a precision of 6×10^{-3}, getting close to the theoretical calculation precision. Moreover, this golden mode may be supported by other decays such as $B_s \to J/\psi f_0(\pi\pi)$ where no angular analysis is required [4].

The $B \to s$ penguins decays : In the standard model the phase $\sin(2\beta_{eff})$ of the penguin dominated $b \to s$ decays is very close to $\sin(2\beta)$ from $b \to ccs$. The former is a very sensitive probe of new physics and the little but persistent discrepancy observed between those measurements is a motivation to reduce the errors on $\sin(2\beta_{eff})$. Extrapolating from [5], the precision on the phase could reach in the single $B^0 \to \phi K^0$ channel 0.05 after 50fb^{-1}. This decay may be supplemented by another interesting measurement also dominated by penguin diagrams thus also sensitive to new physics and whose nice property is to be a “null” measurement : the $B^0 \to \phi\phi$ channel. Although the final state is a vector-vector state requiring an angular analysis, according to the standard model, the penguin and box contributions to the mixing phase should cancel in this process. The expected yields at 50fb^{-1} for $B^0 \to \phi K^0$ and $B^0 \to \phi\phi$ are 10k and 300k events leading to a precision on the measured CP-violation asymmetry of the order of 45×10^{-3} and 25×10^{-3} respectively.

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Seeing $B_s \to \mu\mu$ and $B_d \to \mu\mu$: The channel $B_s \to \mu\mu$ is a very rare decay whose branching ratio is $\mathscr{B} = 3.35 \pm 0.32 \times 10^{-9}$ [6] in the standard model framework. This process could be heavily enhanced thanks to the addition of new diagrams involving new particles in the s-channel, like for example supersymmetric Higgs bosons. In the MSSM, the intervention of these diagrams goes as the power 6 of $tan(\beta)$ making this channel very sensitive. In other models (MCPVMFV [7]), the new diagrams and their phase can lead to a constructive or destructive interference and the final branching ratio can be larger or smaller. Hence, it may be important not only to reach the standard model predictions, what LHCb should be able to do with $10\mathrm{fb}^{-1}$, but maybe also to go below this limit. The BR of $B_d \to \mu\mu$ is smaller than the corresponding B_s decay fraction and LHCb definitely needs to increase its statistics to reach such a level of precision if this is possible which has not yet been proved. Still, the ratio of the two BR is tightly constrained and may clearly distinguish the standard model and the minimal flavor violation cases.

Measuring $B_d \to K^{0*} l^+ l^-$ observables : This is also a rare decay requiring a large statistics to study its properties. The forward-backward asymmetry of the angle of the lepton with the B in the dilepton rest-frame and its zero crossing point can be measured at LHCb. After $10\mathrm{fb}^{-1}$ a precision of $0.22\mathrm{GeV/c}^2$ on q_0^2 should be obtained. The zero asymmetry crossing point is sensitive to many NP models and permits to distinguish several scenarios, but, there exits other clean observables related to the transverse polarisation functions and which can be extracted only with a larger data sample and after an upgrade of the detector.

$B_s \to \phi\gamma$ and right-handed currents : The standard model predicts no right-handed current in the $B_s \to \phi\gamma$ decay. Hence, the quantity $\tan\psi = \left|\mathscr{A}(\bar{B}_{(s)} \to \phi\gamma_R)/\mathscr{A}(\bar{B}_{(s)} \to \phi\gamma_L)\right|$ should be null and can be extracted from $\Gamma_{B_{(s)}\to\phi\gamma}(t) \equiv |A|^2 \exp^{-\Gamma_s t}(\cosh\frac{\Delta\Gamma_s t}{2} - \mathscr{A}^\Delta \sinh\frac{\Delta\Gamma_s t}{2})$, where $\mathscr{A}^\Delta = \sin 2\psi$. To reach a useful sensitivity, a large integrated luminosity is needed. A precision of 0.03 on $\mathscr{A}^\Delta$ may be obtained after $50\mathrm{fb}^{-1}$. The $B \to K^\star e^+ e^-$ channel in the e^+e^- low mass region permits to extract the photon polarisation in the $b \to s\gamma$ processes with a similar precision.

The errors given in the previous examples have been extrapolated to $50\mathrm{fb}^{-1}$ from lower values, typically 2 or $10\mathrm{fb}^{-1}$ considering only the statistical errors, but they show the important step forward performed by using the upgraded LHCb statistics.

3. The detector upgrade

3.1 The new trigger and readout

At the luminosity of $10^{33}\mathrm{cm}^{-2}.\mathrm{s}^{-1}$, the crossing rate is of $30MHz$ with an average number of interactions of 2.3 per crossing. This forces the acquisition to be performed at $40MHz$ and requires a complete change of the readout from the front-end electronics to the event filter (PC) farm to benefit from the large statistics increase. The trigger calculations will be done in the PC farm giving a large flexibility to the processing in order to be adapted to the characteristics of a new physics signal and improving the trigger efficiency especially in the hadronic channels. The figure 1 shows the new scheme. The sub-detectors outputs (right of figure 1) are shaped, zero-suppressed and compressed in order to be sent at $40MHz$ through the GBT system design at CERN [8]. The data are transmitted with optical fibres down to the counting room (safe area of the cavern) to generic data acquisition boards (TELL40) which build the events and produce multi-event packets of data (MEP). The MEP are distributed through a switch to the event filter farm. Each available PC receives a block of several events to be processed (MEP) until it becomes available again. Notice that here the full information is contained in the MEP. As seen on figure 1 (top) a throttling mechanism is necessary either to permit a progressive installation of the PC farm or to reduce the data flow if the number of available PC is punctually not sufficient. A cheap and optimal way of designing this mechanism consists in keeping the information of the present first level trigger (L0) in order to reduce, if necessary, the PC-farm input rate below the expected $40MHz$. Hence the calorimeter and muon trigger processing (that was already running at $40MHz$) is kept almost as it is. Moreover, the large E_t deposits in the hadronic calorimeter identified by the present L0 trigger will be transmitted to the filter farm through an extra TELL40 board. This permits to provide immediately high E_t seeds to the event filter farm and speed up its processing. The GBT protocol should also be used to control the experiment (Experiment Control System or ECS and Time and Fast Control or TFC, on fig. 1) through boards equivalent to the TELL40 but with bidirectional data flows.

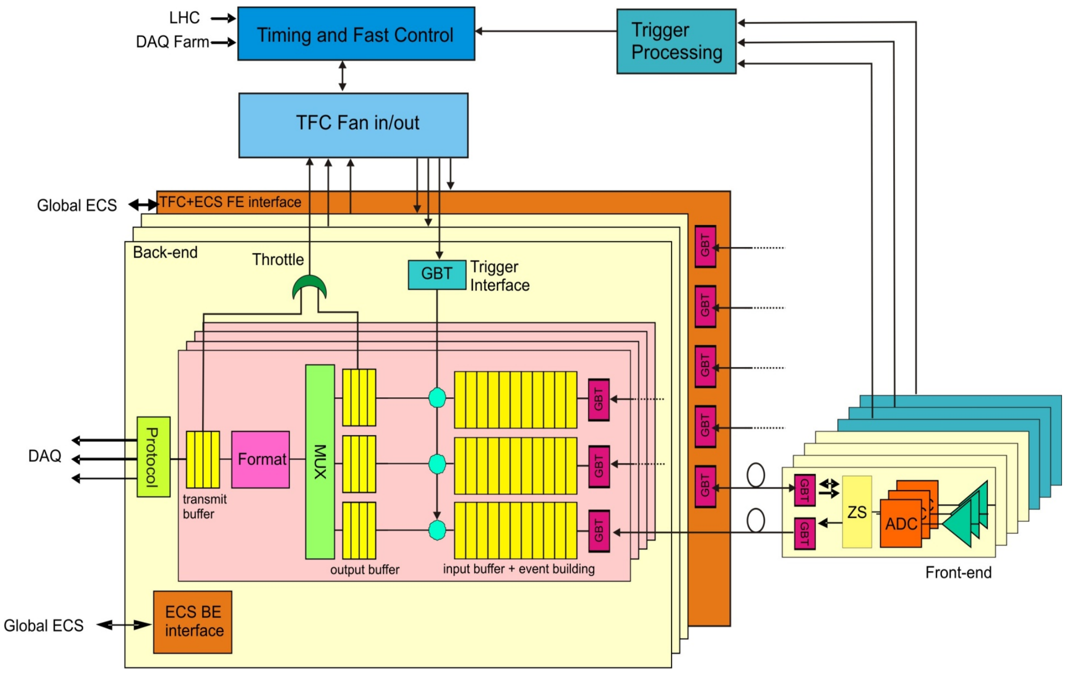

Figure 1: The readout scheme of the upgraded LHCb detector. The front-end is at the right and sends its data to the TELL40 boards which are the main pieces of the new DAQ design. The outputs of the TELL40 are cupper cables connected to a large switch which dispatches the data to the event filter farm.

3.2 Vertexing

The present vertex locator (VELO) is made of R and ϕ silicon strip sensors. The plan for the upgrade is to completely replace the VELO as it will have received already an important total ionising dose. Moreover, the front-end electronics, embarked on the present sensors, has to cope with the readout speed increase and the larger occupancy. The baseline for the next VELO generation is a pixel device made of 26 planes perpendicular to the beam pipe surrounding it to a distance of 7.5mm and based on the Timepix chip from the Medipix family. The chip contains 256×256 pixels of $55 \times 55 \mu m^2$, a plane being made of 8 tiles made of 3 chips each or 2 modules surrounding the beam pipe. This ensures a coverage close to 100%. Each pixel digitises the charge by measuring time over threshold on 4 bits. The sensor seems to resist doses up 500Mrad [10] and good performances were obtained in a test-beam in 2009 [9]. The expected occupancy would reach 6 hits per chip per beam crossing with a mean cluster size of 3 pixels. A 30% data reduction is operated on the data leading to a readout rate of 13.6Gbit.s^{-1}. The foil separating the VELO from LHC primary vacuum is a critical issue as it should ensure safety and a minimal amount of material. A carbon fibre foil is under investigation.

3.3 Tracking

Apart from the VELO, the tracker is built around the so-called TT stations located before the magnet and made of silicon strip sensors. Three other stations (T1, T2 and T3) are positioned after the magnet and consist of an inner (close to the beam pipe) part made of silicon sensors (similar to the TT) and an outer coverage made by straw tubes. Two problems affect the T_i outer region beyond 10^{32}cm^{-2}.s^{-1} : the higher occupancy at larger luminosity starts to reduce the efficiency and the collection of the signal in $50-75$ns leads to the increase of the number of ghosts. This could be corrected by extending the solid angle of the silicon inner region for the second phase of the upgrade, only the front-end electronics should be modified for the first one in order to send the data at 40MHz. Concerning the TT and T_i (inner), the 1MHz electronics is integrated to the sensors. Several solutions are evaluated : either a completed replacement of the sub-detectors or a re-bonding of the electronics on the silicon sensors. A studied solution for the replacement would consist in changing the present technology for layers of tracking fibres readout by SiPM and ASIC located below and above the chambers. This has the advantage of reducing the amount of material in the acceptance and solving part of the radiation issues. Two fibre granularities could be used depending of the regions occupancy (from 250μm and $700-1000\mu$m). The first test-beam results [11] indicate a good spatial resolution and similar performances as the silicon detectors.

3.4 Particle Identification

The present particle identification relies on two Cerenkov detectors (RICH-1 and 2) located before and after the magnet. They cover different ranges in energy and solid angle : RICH-1 (closer to the VELO) has two radiators (Aerogel and C_4F_{10}) and works in the smaller rapidity region, RICH-2 contains CF_4 gas radiator. The light is collected by HPD (Hybrid Photon Detector) whose electronics is embedded inside the photo-tube. To cope with the 40MHz readout, the HPD have to be replaced. The best candidate identified is a multi-anode photomultiplier from Hamamatsu with 64 pixels which has been characterised according to its single-photon response, uniformity, cross-talk and dark current. The stability with temperature and the effect of the magnetic field are looked at. A prototype of the new front-end is being designed, the target being having no pile-up and a very low consumption of the electronics. This solution would permit to keep the detector geometry as it is.

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The gain from the aerogel (RICH-1) could be reduced at higher luminosity because of the multiplicity and of the increase of material it represents. Another more challenging configuration for the upgraded RICH system would consist in removing the aerogel radiator and in putting a time-of-flight sub-detector, called TORCH [12], between the RICH-2 and the calorimeter system (at the present locator of the muon chamber M1, see section 3.5). TORCH would be a quartz wall 7.4×6.1m large and 1cm thick. The photons would be guided in the plate by total reflection up to the edges of the layer, outside of the acceptance where they would be collected most probably by Micro Channel Plates. MCPs are fast photo-detector (in the range $50-70$ps) whose lifetime was a critical issue at LHCb because of the integrated charge expected. Recent developments seem to solve this problem by the introduction of an aluminium protection layer to block ion feedback[13]. The time of flight of the particle would be reconstructed from the position and the detection time of the photons, a precision per single photon of 70ps should be enough ($10-20$ps for the tracks). It is not clear whether TORCH would be ready and is perhaps not essential for the first phase of the upgrage and we may imagine that its installation is postponed to the second one.

3.5 Calorimeter and muon systems

The electromagnetic and hadronic calorimeters and the muon system performances should not be too much affected by the event pile-up. Preliminary calorimeter studies show at 10^{33}cm^{-2}.s^{-1} a degradation on the resolution due the addition, on average, of 14 ADC counts per clusters[2] made of 3×3 cells. This corresponds, at an angle of 100mrad, to a resolution of 14.3% for low energy photons (photons from $B \to D^{*}K$ decay at 400MeV) down to 2.7% in the high energy case (photons from $B_s \to \phi\gamma$ decay at 3.5GeV), to be compared to respectively 7.4 and 2.3% at the present nominal luminosity. The dose expected may be a problem for the inner region of the calorimeter. Two modules have been installed in the LHC tunnel close to our interaction point in order to estimate the effect of radiations on the resolution [14]. The trigger performances will be increased thanks to the availability of the full event at the first level in the PC farm. This will allow to remove the first muon station that is presently located in between RICH-2 and the calorimeter system without affecting the overall performances. Likely, studies are ongoing to decide if the two first constituents of the calorimeter seen by the incoming particles, the Scintillating Pad Detector and the Preshower (two layers of scintillator separated by a lead sheet of 2.5X^0) may also be removed from the upgrade detector optimisation. Apart from the possible removal of these pieces, the front-end electronics is the only modified part of the calorimeter and muon systems. The muon system data are already sent at 40MHz to the counting room. An interface has to be developed so that the muon front-end is able to provide its data to the generic TELL40. The calorimeter system will be more deeply modified. To keep the present photo-multipliers, it is necessary to reduce the gain by a factor 5. The front-end electronics should compensate for this this with the same noise constraints, typically 1 ADC of noise per channel. The first prototypes for the analog and digital parts of the electronics have been produced recently but the simulations seem to show the feasibility of such a system. To competing analog part are being developed in parallel, either based on discrete components and on an ASIC. The digital electronics is designed around a flash technology FPGA from Actel, in order to resist the level of radiations in the cavern.

[2]The calorimeter electronics measures E_t. One ADC count is $2.5MeV$.

4. Conclusion

It is foreseen to start the first phase of the upgrade of the LHCb detector in 2015. The optimisation is converging towards a more efficient detector able to cope with the new beam conditions and with the radiations expected in the cavern. The aim is to increase the instantaneous luminosity by a factor 5 with respect to the nominal rate and the overall objective is to record of the order of 50fb^{-1}. This data sample should help us in identifying even small new physics effects and we may hope that its manifestations at LHC will be such that we will be able to understand its origins. A second phase is already planned and will most probably require new improvments (new outer tracker, TORCH, ...). But, the larger step forward will be done before and consists in having a full detector readout at 40MHz with a full software trigger. This will increase the detector acceptance for interesting channels and tremendously improve the detector flexibility to focuse on any sign of new physics.

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